

## OPTICAL FREQUENCY DIVISION MULTIPLEXING

### CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority from US Provisional application Serial No: 60/201,314, filed May 2, 2000, which is incorporated herein by reference.

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### FIELD OF THE INVENTION

The present invention relates generally to optical communication systems, and more particularly to frequency division multiplexing in optical communications systems.

### BACKGROUND OF THE INVENTION

An optical communication system, as used herein, refers to any system that uses 10 optical signals to convey information across an optical waveguiding medium. Such optical systems include, but are not limited to, telecommunications systems, cable television systems, and local area networks (LANs). Many optical communication systems are configured to carry an optical channel of a single wavelength over one or 15 more optical waveguides. To convey information from plural sources, time-division multiplexing (TDM) is frequently employed. In TDM, a particular time slot is assigned to each information source, the complete signal being constructed from the signal portion collected from each time slot. While this is a useful technique for carrying plural information sources on a single channel, its capacity is limited by electronic state of the art technology, and fiber transfer properties such as dispersion, non linear effects, etc. 20 The effects of these phenomena generally require signal regeneration subsystems along the fiber line, such as erbium doped fiber optical amplifiers (EDFAs), which are commonly used for that purpose. An alternative solution is to generate high peak power laser pulses, which limit the generated power because of the four wave mixing effect. Consequently, other techniques have been developed to increase the capacity of existing 25 optical waveguides.

Wavelength division multiplexing (WDM), or Dense WDM (DWDM) or Coarse WDM (CWDM), are known methods for increasing the capacity of existing fiber optic networks. In general a WDM system employs plural optical signal channels, each channel being assigned a particular channel wavelength. In a WDM system, optical signal channels are generated, multiplexed to form an optical signal comprising the individual optical signal channels, transmitted over a single waveguide, and

individual optical signal channels, transmitted over a single waveguide, and demultiplexed such that each channel wavelength is individually routed to a designated receiver. Through the use of optical amplifiers, such as doped fiber amplifiers, plural optical channels are directly amplified simultaneously, facilitating the use of various 5 WDM configurations in long or long distance optical communication systems.

In many applications, such as optical LANs, cable television subscriber systems, and telecommunications networks, there is a need to route one or more channels of a multiplexed optical signal to different destinations. Such routing occurs when optical channels are sent to or withdrawn from an optical transmission line, e.g., for sending 10 optical channels between a terminal and an optical bus or routing long or short distance telecommunications traffic to individual cities or customers. This form of optical routing is generally referred to as "add-drop multiplexing".

In prior art systems, the amount of information that can be carried by one channel of a WDM fiber optics transmission line is in a bandwidth reaching the value of 15 about 10 GHz. Considerable efforts are being made to increase the transmitted information bandwidth to 40 GHz. Transmission of a 10GHz bandwidth, for example, may be achieved either by modulating a diode laser source directly or by using a continuous wave (CW) laser and modulating the data by means of an external electro-optical intensity modulator. However, in order to add and drop or extract part of 20 the information from one of the WDM channels, one must first convert the entire optical signal to an electrical signal in accordance with the conventionally accepted communication protocols, and only then, extract the specific data needed. Thus, a disadvantage of the prior art is that an increase in the transmitted bandwidth requires a comparable increase in the bandwidth capabilities of the electronics components, 25 increase the amount of reshaping signal components along the fiber lines, which in turn substantially increases the cost of the system.

Another disadvantage of the prior art is that the actual separation between two laser lines of the WDM grid is around 100 GHz, with current efforts to decrease this 30 value to 50 GHz. Factors, such as electronic time response, jitter and drift of the laser, limit the practical bandwidth of one WDM laser to values lower than the bandwidth transmission capabilities. Thus, the wide optical bandwidth is not used to its fullest extent.

Still another disadvantage of the prior art is the fact that as the bandwidth of information transmitted is increased, problems, such as fiber dispersion, polarization

dispersion as well as non-linear effects in the fiber, start to play a major factor in decreasing the distance over which the information may be transmitted.

## SUMMARY OF THE INVENTION

The present invention seeks to provide methods for multiplexing in optical 5 communications systems, which overcome the limitations of the prior art. The present invention employs optical frequency division multiplexing in a novel way, wherein optical information is modulated by creating an additional family of optical carriers on each color (wavelength) of the WDM carriers. The system may be described as a type of "carrier on carrier" system, wherein the optical carrier (WDM) is separated (i.e., shifted) 10 by a small additional amount with another carrier defined by a resonant electro-optical modulator frequency.

Each "family member" has an individual optical ID. The aggregate information for each WDM channel is divided into "sub-channels", each of which operates at a relatively low bit rate of approximately 0.5-2 GHz, in accordance with individual 15 customer or user needs, for example. The optical information emanating from each individual laser channel of the same wavelength is up-converted in the frequency domain with a different carrier frequency (separated, for example, by about 3 GHz). The up-conversion is preferably accomplished by means of resonant electro-optical modulators, in which case the frequency division multiplexing comprises resonant dense 20 frequency division multiplexing. The up-conversion of the individual "sub-channel" may attain a resonant frequency carrier per individual WDM laser approaching 70-80 GHz, a significant improvement over the prior art. With the emerging technology of polymer materials as the crystal to be used for electro-optical modulators, frequencies as high as 25 120 GHz. have been achieved, which will further increase the significance of the present invention.

All the optical channels are preferably inserted in one fiber transmission line, as in typical WDM system architectures. However, in contrast to the prior art, in the present invention it is possible to add or drop sub-channels at any point along the line while still in the optical domain. This may be achieved by down-conversion in the 30 frequency space, in a format or protocol compatible with the up-conversion units, and filtering the signal with a bandwidth around 0.5-2 GHz, instead of about 10 GHz or higher as in the prior art. The down-conversion may be achieved by using the same type of resonant electro-optical modulators.

In the present invention, the amount of data transmitted in one WDM channel may be increased by a factor of 2-3, while lowering the operating frequency of the associated electronics, detectors and lasers (by at least a factor of 5). The amount of data processed for each channel is much lower in comparison to the prior art, and there is no  
5 need to process the entire data in order to retrieve an individual group or sub-channel. The methods of the present invention may be implemented separately at each WDM channel.

In the WDM prior art, wherein the aggregate bandwidth, electronically multiplexed, modulates the laser directly (or by an external modulator with a CW laser),  
10 an entire channel may be shut down in the event of a catastrophic failure of the laser source or the modulator. In contrast, in the methods of the present invention, only partial information may be non-transmittable in the event of a catastrophic failure of the laser source.

In the prior art, in order to achieve high data modulation rates via laser switching,  
15 driving currents may be very high, leading to high power emission losses and a decrease in the stability of the laser. The use of external modulators at high rates also has similar disadvantages, for example, the driver is extremely bulky, sophisticated electronic control circuitry is required, power consumption is high, and the cost is extremely expensive.

20 In contrast, in the present invention, since the laser operates at 0.5-2 GHz, the modulation depth is much higher than laser sources operating at high bit rate. This means that for a given power, the transmission distance is much longer in the present invention than in the prior art

25 The present invention may increase the number of optical carriers and the overall information bandwidth per channel for many kinds of optical communication systems, such as, but not limited to, non-WDM, coarse WDM and dense WDM (DWDM) networks.

30 There is thus provided in accordance with a preferred embodiment of the present invention a method for division multiplexing of optical signals, the method including modulating at least one wavelength of a carrier (e.g., a WDM carrier) of optical information, by optical frequency division multiplexing the at least one wavelength.

In accordance with a preferred embodiment of the present invention the modulating includes creating at least one additional optical information carrier on the at least one wavelength of the carrier.